

THE EFFECT OF POTASSIUM ON THE UPTAKE OF ^{137}Cs IN FOOD CROPS GROWN ON CORAL SOILS: COCONUT AT BIKINI ATOLL

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Abstract—The soils of Bikini Atoll ($11^{\circ} 35' \text{N}$, $165^{\circ} 25' \text{E}$) were contaminated by fallout from a thermonuclear explosion in 1954. Today, in the absence of any treatment, intake of ^{137}Cs via the terrestrial food chain could account for 70% of the radiological dose received by a returning population. Therefore, we examined the effectiveness of potassium applications, alone and combined with nitrogen and phosphorus, in reducing ^{137}Cs uptake by coconut (*Cocos nucifera* L.), a major food crop. Mean pretreatment concentrations of ^{137}Cs in “drinking-nut” meat of ~17-y palms ranged from ~0.5 to 7.0 kBq kg^{-1} (~14 to 190 pCi g^{-1}) (wet mass) in the seven primary experiments reported. These values were reduced to ~0.06 to ~1.0 kBq kg^{-1} (~1.6 to ~27 pCi g^{-1}) following soil additions of potassium-chloride at rates from 670 to 6270 $\text{kg potassium ha}^{-1}$. Major reductions were complete within 9–12 mo after single large applications and persisted for at least 3 y. Proportional reductions in associated drinking-nut fluid and in mature “copra nut” meat from the same palm also occurred. Comparable but shorter-lived reductions occurred in grass and herbaceous species beneath the palms. A combined nitrogen-phosphorus treatment had no additive effect in the presence of potassium but, by itself, reduced plant uptake by about 50%. The persistence of this effect suggested that phosphorus alone was the major factor. Periodic additions of potassium at rates of ~1000 kg ha^{-1} would provide a feasible and highly effective means of reducing ^{137}Cs in coconut food products. *Health Phys.* 62(6): 496–511; 1992

Key words: ^{137}Cs ; soil; contamination, environmental; food chain

INTRODUCTION

A THERMONUCLEAR device, code-named BRAVO, detonated at the northwest end of Bikini Atoll, 1 March 1954, resulted in radioactive deposition on the northern and eastern islands of the atoll. Thus, the resulting current inventory of ^{137}Cs in the soil of the two principal residential islands, Bikini and Eneu, represents an aged source term.

Natural environmental processes have redistrib-

uted the surface-deposited radionuclides. In the case of plant-absorbed elements, downward movement has been countered in some degree by recycling through vegetation (Koranda et al. 1978). In addition, numerous construction operations during the subsequent years of testing, followed by cleanup and resettlement activities after 1969, caused large-scale disturbance of the surface soil. The generalized pattern of ^{137}Cs distribution in soil, a logarithmic decrease downward, is similar on both islands (Fig. 1) despite a nearly 10-fold difference in concentration.

Detailed information on the radionuclide concentrations in foods and soil at Bikini have been given in Robison et al. (1982a, 1988), together with the potential radiological dose via all exposure pathways for people resettling the atoll. In the absence of any treatment, ^{137}Cs would be responsible for more than 90% of the estimated dose (Robison et al. 1982a; Robison 1983) with more than 70% of the total via the terrestrial food chain. Locally grown coconut would be a major contributor. The second most important pathway would be external exposure from ^{137}Cs gamma radiation. Thus, either eliminating ^{137}Cs from the soil column or reducing its uptake by food crops would substantially reduce the estimated dose to inhabitants and profoundly affect decisions about resettlement options.

The initial objective of this study was to identify a means of reducing plant uptake of ^{137}Cs in established coconut palm groves that could be applied to Bikini and other atolls. When soil applications of potassium proved effective, the objective changed to determining the magnitude and persistence of such reductions, as related to the quantity of potassium applied and its interaction with other plant nutrients.

BACKGROUND

Soils of deep ocean atolls differ from most continental soils in that the mineral matrix consists almost solely of sand and coarser-size particles of calcium carbonate, as calcite and aragonite, containing small amounts of substituted magnesium and strontium. Organic matter content of the surface layer varies from a trace to more than 10% and is the sole source of cation-exchange capacity. Silicate clays appear undetectable

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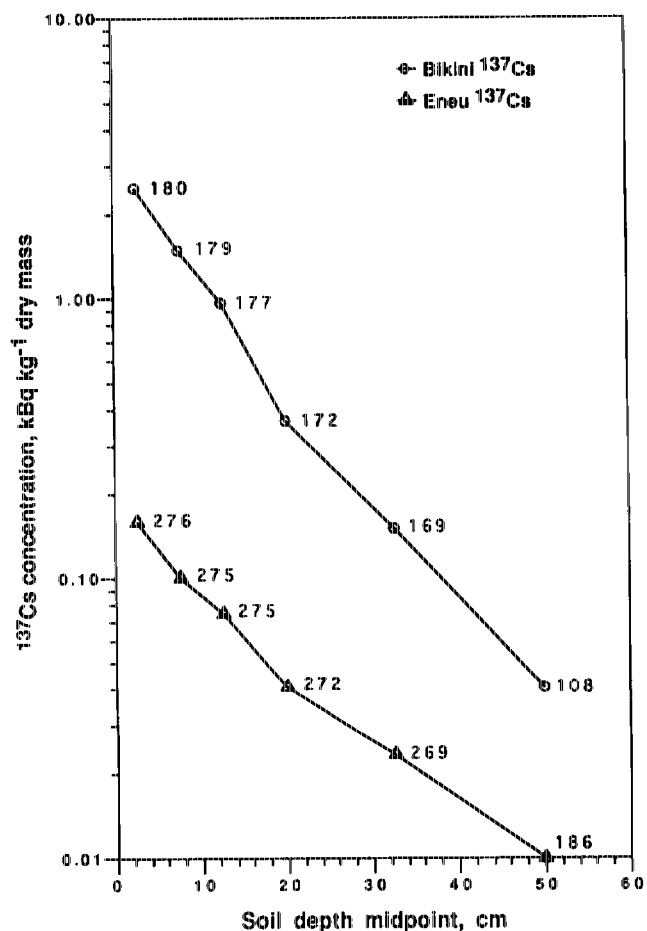


Fig. 1. Median distribution of ^{137}Cs with soil depth on Bikini and Eneu Islands.

although trace amounts from global dust presumably occur. Analyses of three representative profiles from the stable island interiors illustrate the range in chemical properties of well-developed soils (Table 1). All are calcareous with proportions of total magnesium and strontium varying in accord with biological origin and weathering intensity. Organic matter is relatively high in the surface but decreases abruptly through a narrow transition zone. Calculated carbon:nitrogen ratios are about 10:1 to 13:1, indicating an advanced stage of decomposition. Total phosphorus is highly variable in amount, representing input by nesting sea birds at some time in the past.

Total potassium in atoll-soil materials is low; the average for several atolls reported by Fosberg and Carroll (1965) is only 300 mg kg^{-1} . Exchangeable or extractable potassium is highest in the 0–5-cm layer, a result of both spray input and cycling by vegetation, but diminishes rapidly downwards (Table 1).

The concentration of stable cesium in sea water is about $3 \times 10^{-13} \text{ kg cesium kg}^{-1} \text{ water}$ (vs. $3.9 \times 10^{-7} \text{ kg potassium kg}^{-1} \text{ water}$). Hence, both the total and

exchangeable quantities of ^{137}Cs in atoll soils must be very small, although analytical data are lacking. Maximum total concentrations of ^{137}Cs in the Bikini surface soils now range between 0.5×10^{-12} and $3 \times 10^{-12} \text{ kg } ^{137}\text{Cs kg}^{-1} \text{ soil}$ (Fig. 1 and Table 1), or about 8 orders of magnitude lower than the maximum surface concentrations of extractable or exchangeable potassium (Table 1; also Stone in Emery et al. 1954). Only 3–5% of the ^{137}Cs remaining from 1954 is exchangeable, even with sequential extractions.[†] Although this appears contrary to expectations based on laboratory studies of cation exchange, such studies usually involve solution concentrations of 10^{-1} to 10^{-3} M , and analytical accuracies to perhaps 10^{-4} . Hence, retention of any cation in the range of 10^{-12} would be undetectable.

In contrast to many observations in acid to neutral continental soils, plant uptake of ^{90}Sr from atoll soils is greatly limited by the overwhelming dominance of calcium, by the potential for replacing calcium in the CaCO_3 matrix, and by the appreciable amount of stable strontium (Table 1). The uptake of ^{90}Sr in coconuts is unaffected by the addition of potassium, as might be expected. We have not evaluated the effect of the potassium treatment on $^{239+240}\text{Pu}$ or ^{241}Am found in the atoll soils but it is unlikely that they would be affected.

It is known that addition of potassium to nutrient solutions containing cesium greatly reduces uptake of cesium (Cline and Hungate 1960; Middleton et al. 1960; Handley and Overstreet 1961; Nishita et al. 1962; Wallace et al. 1983). Where both elements are available, plants selectively absorb potassium and discriminate against cesium. In potassium-deficient media, cesium acts as a replacement for potassium, but only to a limited degree, with plants failing well short of maturity (Menzel 1954; Cline and Hungate 1960; Middleton et al. 1960; Wallace 1970; Wallace et al. 1983). These findings have only limited relevance to Bikini soil-plant systems in view of the very wide ratio between available forms of the two elements there.

Likewise, the extensive literature on ^{137}Cs retention in soils with silicate clays is largely irrelevant to atoll soils. Of greater interest is the evidence that cesium that is bound to organic matter, although largely nonexchangeable, is far more available for plant uptake than is cesium retained by clays (Barber 1964; Menzel 1965; Fredriksson et al. 1966; D'Souza et al. 1972; D'Souza et al. 1980). This is borne out by the high plant-soil concentration ratios (CR) observed at Bikini and other atolls of the northern Marshall Islands (Robison et al. 1982a,b, 1988). Ratios of 1:5 (^{137}Cs , kBq kg^{-1} wet mass: ^{137}Cs , kBq kg^{-1} dry soil) contrast with values of about 10^{-1} to 10^{-3} reported in Ng et al.'s (1982) extensive review of non-atoll soils.

Although a suppressive effect of added potassium on plant uptake of ^{137}Cs from atoll soils seemed highly probable, the only prior evidence known to us was that of the University of Washington investigators (Walker

[†] Robison, W. L. Unpublished data (1991). Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550.

Table 1. Composition of coral soils from Bikini and Eneu Islands.

Island location and depth (cm)			Total ^a							Particles sized <0.5 mm (%)	
	pH ^a	¹³⁷ Cs ^b (kBq kg ⁻¹)	⁹⁰ Sr ^c (kBq kg ⁻¹)	Strontium (%)	Calcium (%)	Magnesium (%)	Phosphorus ^c (%)	Nitrogen (%)	Organic matter ^d (%)	Extractable potassium ^e (mg kg ⁻¹)	
<i>Bikini No. 1</i>											
0-5	7.7	10.4	2.4	0.38	30.4	0.95	1.35	0.64	14.4	79	11.5
5-10	7.8	3.2	2.7	0.39	30.8	0.89	1.28	0.62	13.2	26	
10-15	7.9	1.3	2.3	0.39	30.9	0.89	1.29	0.63	12.3	20	9.5
15-25	7.9	0.82	1.4	0.40	31.9	0.86	1.17	0.50	10.6	23	11.7
25-40	8.3	0.13	0.89	0.39	34.3	1.28	0.67	0.19	4.5	4	6.3
40-60	8.4	0.041	—	0.31	34.5	2.05	0.16	0.11	1.6	3	0.6
<i>Bikini No. 2</i>											
0-5	7.8	4.4	2.4	0.40	31.0	1.02	0.82	0.49	10.7	50	5.7
5-10	8.0	2.0	2.7	0.40	32.4	1.09	0.71	0.46	8.5	24	3.7
10-15	7.9	0.78	2.3	0.38	33.1	1.18	0.56	0.35	7.4	24	3.3
15-40	8.2	0.16	1.2	0.38	34.7	1.79	0.32	0.11	1.6	6	1.1
<i>Eneu No. 1</i>											
0-5	7.7	0.3	0.085	0.32	32.0	1.74	0.085	0.30	5.1	41	2.3
5-10	8.0	0.25	0.096	0.34	32.6	1.76	0.055	0.35	5.6	20	1.6
10-15	8.0	0.093	0.10	0.31	34.4	2.08	0.037	0.17	2.6	9	0.8
15-25	8.4	0.0037	0.093	0.28	34.0	2.40	0.016	0.06	0.9	1	0.3
25-40	8.7	0.0037	0.089	0.28	34.4	2.48	0.014	0.05	0.8	1	0.2
40-60	8.9	0.0074	—	0.30	33.3	2.37	0.015	0.03	0.6	<1	0.1

^a pH in water.^b 1 kBq kg⁻¹ of ¹³⁷Cs = 3.1 × 10⁻¹³ kg cesium kg⁻¹.^c The ⁹⁰Sr activities are the mean of 55-63 sites on Bikini and 37-40 sites on Eneu. The activity at locations 1 and 2 on Bikini and Eneu Islands was not determined.^d Stable cesium was below the detection limit of 1.3 mg kg⁻¹.^e High phosphorus values indicate ancient guano deposition.^f Organic matter by wet oxidation.^g Extractable N ammonium acetate.

et al. 1961).[†] This was based almost entirely on pot culture studies of soils from Rongelap Atoll which also was contaminated by BRAVO fallout.

METHODS

Field sample questions

Field studies and sampling were conducted during quarterly to semiannual visits to the atoll. Eight successive studies (Table 2) were established in bearing coconut groves. The groves, of a large-fruited variety originally from Yap Island, had been planted in 1970 to 1972 after clearing existing vegetation. Tending of groves ended in 1978. Thus, each of our experiments entailed clearing of regrowth shrubs and volunteer coconuts. Use of a bulldozer caused some degree of soil disturbance. Ordinary commercial fertilizers were broadcast on the soil surface, either entirely at the beginning of a study or periodically, as described in Table 2. Regrowth of competing shrubs was controlled occasionally, either by mechanical crushing, mowing or hand clearing.

Samples were collected prior to the first application of fertilizers and usually at 3- to 6-mo intervals thereafter. The basic coconut sample was a composite of five

to eight "drinking nuts" from an individual palm. As not every palm bore nuts at the drinking stage at each collection period, the numbers of sampled palms per experiment or plot often varied. Mature copra nuts were sometimes collected in the absence of drinking nuts or, on two occasions, paired with drinking-nut samples from the same palms for comparative purposes.

The husked nuts were punctured in the field and the fluid (liquid endosperm) from each was measured and pooled for the final sample. Both punctured nuts and fluid were frozen within 3 to 4 h and transported in that condition to Lawrence Livermore National Laboratory (LLNL) for analysis of ¹³⁷Cs and other gamma-emitting nuclides.

Laboratory procedures

At LLNL the nuts were cracked and the meat removed, dried by lyophilization, and ground in a blender. The meat was packed into 8.0-cm diameter × 4.6-cm-high aluminum cans. The coconut fluid that was collected in the field was first reduced in volume by evaporation and then canned for analyses. Most gamma analyses were performed in the LLNL facility which consists of 14 high-resolution solid-state detectors and multichannel analyzers. Blind duplicates and standards were included in each sample batch with a requirement that agreement be within 10% for acceptance. Similar quality-control standards and cross-

[†] Personal communication (1984), Walker, R. B. Suppressive effect of added potassium on plant uptake of ¹³⁷Cs in pot culture studies. University of Washington, Seattle, WA.

Table 2. Synopsis of design, treatments, and characteristics of experiments with bearing coconut palms.

Experiment number	Begun (y)	Duration (mo)	Design, treatment, and gross plot area	Fertilizer			Minimum treated radius (m)	
				Carrier	Total applied kg ha ⁻¹			
					Nitrogen	Phosphorus		Potassium
<i>Eneu Island</i>								
I	1980	112	One 0.065 ha 4-palm plot. Ten applications of nitrogen-phosphorus-potassium 3 y ⁻¹ .	13.7-6.4-10 ^a	2870	615	1830	8.5
II	1983	90	Four 8.5-m radius single-palm plots (0.023 ha); roots unconfined. Thirteen applications of nitrogen-phosphorus-potassium 3.5 y ⁻¹ .	13.7-6.4-10 ^a 16-16-16	2640	975	2190	8.5
<i>Bikini Island</i>								
III	1983	90	Five 8.5-m radius single-palm plots (0.023 ha); roots unconfined. Thirteen applications of nitrogen-phosphorus-potassium 3.5 y ⁻¹ .	13.7-6.4-10 ^a 16-16-16	3300	1080	2400	8.5
IV	1985	33	Potassium × nitrogen-phosphorus factorial, 3 × 2 × 2 replication. Ten-palm row plots, 0.16 ha with 8.5-m separations. Four applications 9 mo ⁻¹ .	Potassium-chloride (K ₁) Potassium-chloride (K ₂) 26-26-0 (NP ₁)	0 530	0 230	1260 2520 0	8.5
V	1986	45	K ₀ vs. K ₁ , 2 × 5 replication, complete randomization. Single-palm plots, 73 m ² , with subsoiled boundaries. Single application.	Potassium-chloride	0	0	6270	Not applicable
VI	1987	33	K ₀ vs. K ₁ , unreplicated. Ten-palm plots with treated borders, 0.16 ha. Single application.	Potassium-chloride	0	0	3740	17 ^b
VII	1988	27	K ₀ vs. K ₁ , unreplicated. Twenty-palm plots with treated borders, 0.408 ha. Single application.	Potassium-chloride	0	0	670	17

Table 2—Continued

Experiment number	Begun (y)	Duration (mo)	Design, treatment, and gross plot area	Fertilizer				Minimum treated radius (m)
				Carrier	Total applied kg ha ⁻¹			
					Nitrogen	Phosphorus	Potassium	
VIII	1989	12	K ₀ vs. K ₁ . Experiment IV area reblocked and boundaries sub-soiled. Two blocks, 0.63 and 1.9 ha, re-fertilized over all. Two blocks, 0.63 each, are controls and contain Experiment IV controls. Single application.	Potassium-chloride	0	0	1120	Not applicable

^a "Osmocote, tropical" plastic encapsulated pellets.

^b 8.5 m at plot ends.

counting at LLNL were imposed on those samples analyzed at other laboratories. In some instances, ⁴⁰K determinations were used to estimate total potassium (1.0 Bq ⁴⁰K ≈ 22.27 mg potassium). However, the shorter counting times suitable for ¹³⁷Cs often yielded erratic or nonreproducible ⁴⁰K values for individual samples, contributing heavily to the variances of population means.

All ¹³⁷Cs and ⁴⁰K concentrations of coconut and other plant material were converted back to an original wet weight basis, except as otherwise specified.

Field experiments

Experimental design, treatment, and plot size varied over the 9 y of installation (Table 2); specific descriptions follow.

Experiment I. As an outgrowth of initial monitoring efforts, a single four-palm plot, 26 × 26 m, was fertilized with a complete nitrogen-phosphorus-potassium fertilizer on 10 occasions over a 3-y period (Table 2). A slow-release fertilizer, Osmocote-Tropical,[§] consisting of plastic-encapsulated pellets, was chosen to ensure a continuous nutrient supply between successive visits. Sampling had begun prior to the first application and still continues. Untreated, less-intensively monitored palms nearby served as informal controls.

Experiments II and III. These are parallel installations on Eneu and Bikini Islands, respectively. For each, four or five well-separated palms were selected from previously monitored populations to represent the maximum ranges of observed ¹³⁷Cs concentrations in drinking nuts. A combined fertilizer, usually 1:1 Osmocote and readily soluble 16-16-16, was broadcast

13 times over an 8.5-m radius around each palm. Untreated palms, separated in distance around the island, served as controls.

Experiment IV. Two contiguous blocks of 17- × 94-m plots, each separated by either one or two 8.53-m-wide untreated strips, were established in a ~4-ha area of newly cleared grove. The selected area represented the highest average ¹³⁷Cs surface-soil concentrations on Bikini Island, 2.6 to 3.7 kBq kg⁻¹ (70 to 100 pCi g⁻¹), as determined by a 1978 aerial radiological survey (Tipton and Miebaum 1981). The design was factorial: two rates of applied potassium, with and without addition of a combined nitrogen-phosphorus treatment, in two blocks (Table 2). The fertilizers were distributed with a small battery-driven centrifugal spreader mounted on the back of a truck. Several passes were required to distribute the designated quantities. The fertilized strip was 17 m wide, extending from the trunks of one 10-palm row to those of a third row, with only the center row (fertilized on both sides) being sampled until the 33 mo of the study. Four equal applications were made between February and December 1985.

The original experimental design was terminated at 33 mo. At that time, the 8.5-m-wide separation strips on either side of the K₁NP₀ and K₁NP₁ plots in one block were treated with potassium-chloride at the K₁ rate, thus doubling the previous plot width. Doing so extended potassium-treated soil to the edges of the K₀NP₁ plot, which was between the other two, and hence to 8.5 m from the NP₁ sample row. Eleven months later, paired samples of drinking nuts and copra nuts were collected from individual palms in all of the original plots.

Three plots remained unaffected by the further treatment at 33 mo and again at 51 mo when Experi-

[§] Osmocote-Tropical, Grace Serra Chemical Company, 1001 Yosemite Drive, Milpitas, CA.

ment IV was converted to Experiment VIII. Mean ^{137}Cs values from these plots are shown as an extension of the 0–33-mo data.

In addition to coconut samples, bulk samples of a dominant understory grass, *Eustachys petraea* (Sw.) Desr., were collected from each plot at 9, 18, 21, and 30 mo. Entire stems were clipped above the ground line along plot centers. Fleshy leaves of moonvine, *Ipomea macrantha* R&S, were also collected on the first three dates. The bagged samples were frozen and transported to LLNL where they were oven-dried, ground, and analyzed, as was the coconut meat.

Experiment V. One year after the area of Experiment IV had been cleared, 25 palms in an unused margin were rated individually for apparent vigor and fruitfulness. Ten were selected and assigned randomly to one of two treatment groups, a control group, and “super-potassium” group—an application of 6,270 kg potassium ha^{-1} aimed at maximizing the magnitude and rapidity of ^{137}Cs decrease. Single palm plots, $\sim 8.5 \times 8.5$ -m square, were created by subsoiling about 80 cm deep midway between rows in both directions. This is below the depth of most horizontal roots and so restricted absorption from the surface soil to within pilot boundaries. Subsequent observations of root regrowth led to subsoiling again at 12 and 24 mo and at 6-mo intervals thereafter.

The small plot size required hand spreading of the coarse-crystal potassium-chloride. To increase uniformity, the total per plot was divided into thirds and each third spread over the entire plot by a separate worker.

Experiment VI. Other studies demonstrated that coconut roots extend radially to at least 24 m, with large numbers of absorbing roots outside the 8.53-m minimum radius of treatment in Experiment IV. Thus, we established Experiment VI, aimed at maximizing the width of treated soil surrounding the sampled palms within the limitations of the grove area then available. Each of the two sample plots consisted of two rows of five palms, surrounded by a similarly treated border, 17.1 m wide on the sides and 8.5 m on the ends. The treatments, 0 and 3,940 kg potassium ha^{-1} , were randomized but unreplicated. Fertilizer distribution was as in Experiment IV.

Measurement of ^{137}Cs surface gamma emission prior to selection of this site indicated row means of ~ 7.74 to $10.3 \text{ nC kg}^{-1} \text{ h}^{-1}$ (~ 30 to $40 \mu\text{R h}^{-1}$), only moderately less than in adjacent Experiment IV. Nevertheless, samples of drinking nuts were much lower in ^{137}Cs . Two palms at one end of the control plots were excluded from data summaries because their drinking nut concentrations were more than three standard deviations greater than the mean of all other untreated palms.

Experiment VII. The study design duplicates that of Experiment VI but with palms much higher in ^{137}Cs . The measurement plots were larger, four rows \times five

palms, with 17.1-m-wide borders on all sides. The treatment rate, however, was much lower: 670 kg potassium ha^{-1} . The application was as in Experiments IV and VI.

Experiment VIII. As noted, Experiment IV was altered somewhat after 33 mo by additional treatment in one block. The results prompted an expanded treatment.

Accordingly, 51 mo after establishment of Experiment IV, the entire area was divided into four units or blocks that were separated by periodically subsoiling the boundaries to a depth of 70 to 80 cm. Two 0.64-ha units remained untreated and included four unaltered plots from original Experiment IV: K_0 , K_0 , $\text{K}_0 + \text{NP}$, and K_2 . The other two units, 0.64 and 1.9 ha in size, were treated overall with coarse-crystal potassium-chlorine at the rate of 1,120 kg potassium ha^{-1} , using a tractor-mounted swinging-tube spreader. Visual estimates of the crystal distribution indicated that coverage was complete.

Samples collected immediately before and 12 mo after this potassium application represent a variety of previous treatments. We have limited detailed analysis to only those unaltered “interior rows” of the originally designated Experiment IV plots and to only those palms that provided drinking-nut samples both at the time of refertilization (51 mo) and 12 mo thereafter. For present purposes, we considered the palms as individual sample units with paired before-and-after determinations of ^{137}Cs .

Data analysis

Experiments I, II, and III have no formally designated controls but data from monitored unfertilized palms nearby assure that the large systematic reductions in ^{137}Cs concentrations occurred only after treatment.

Analysis of variances (ANOVAs) of results from Experiments IV and V were conducted using SAS software (SAS Institute, Inc. 1985). An initial ANOVA of the entire Experiment IV data set (33 mo) by a repeated measures design revealed significant interaction between treatment and time and between the potassium and nitrogen-phosphorus treatments. Accordingly, further analysis dealt with each of the sampling times separately. These ANOVAs are based on weighted plot means inasmuch as the number of palms contributing varied, usually between three and nine. Duncan's Multiple Range Tests ($p = 0.10$) provide validation for the graphic presentations.

A separate ANOVA of drinking nut vs. copra nut data collected at 42 mo was conducted. The sample was limited to those palms bearing both drinking nuts and copra nuts. The relationships between copra nut meat and drinking-nut meat, and between copra nut meat and fluid were examined by regression analysis.

An earlier analysis of covariance (ANOCOVA) of Experiment V demonstrated that large pretreatment differences in ^{137}Cs among individual palms signifi-

cantly affected posttreatment values but only for the first 5–9 mo. Accordingly, the covariant was omitted from the present ANOVAs. The small and variable number of individual palms (3–5) contributing to each periodic mean indicated use of standard errors rather than Duncan's tests as measures of variation in the graphic presentations.

Standard errors for palms within plots are shown in the graph of Experiment VI and VII results. In view of the obvious effects of treatment, a planned "paired plot" analysis occurring both before and after fertilization, within treatment, appeared redundant.

For Experiment VIII, the differences among means of the paired before and after samples were examined by unpaired *t*-tests.

RESULTS

Although drinking nuts were selected by Marshallese climbers, they represent a substantial range in maturity and volume of both meat and fluid, as well as ^{137}Cs concentration. A synthesis of various field and laboratory observations indicates that ^{137}Cs concentrations in meat increase progressively from the earliest drinking-nut stage onward, with an eventual copra nut to "modal drinker" ratio of 1.6:1, as described later. Meat thickness increases and moisture content decreases during this development. Fluid volume increases for a time through the "young drinker" stage as the nut continues to enlarge but then decreases as the meat thickens. Fluid to meat ^{137}Cs CR increases rapidly from around 0.2 to 1- to 0.25 to 1-in "young drinkers" with only traces of meat, to 0.5 to 1- to 0.7 to 1-in maturing copra nuts, finally approaching 1 to 1 in old copra nuts in which fluid no longer completely fills the nut cavity. Such changes contribute heavily to sampling variability in both drinking and copra nuts, among and within collection dates.

Experiments I, II, III

Variation among dates prior to treatment is due in part to a greater allowable range in what was then collected as "drinking nuts," and in part to unrecorded bulldozer clearing to facilitate access.

Although the three studies represent a wide range in pretreatment ^{137}Cs concentrations, from ~ 0.37 to $\sim 7.4 \text{ kBq kg}^{-1}$ (~ 10 to $\sim 200 \text{ pCi g}^{-1}$) in drinking-nut meat, the patterns of decrease after repeated applications of nitrogen-phosphorus-potassium fertilizers are similar (Figs. 2–4). The greater the initial concentration, the greater the absolute decrease to near-asymptotic levels characteristic of individual palms (Figs. 3 and 4). Palms initially low in ^{137}Cs , $\leq 1.85 \text{ kBq kg}^{-1}$ ($\leq 50 \text{ pCi g}^{-1}$), reached the lowest ^{137}Cs activity levels, which often fell below those of naturally-occurring ^{40}K concentration of $\sim 0.11 \text{ kBq kg}^{-1}$ ($\sim 3 \text{ pCi g}^{-1}$).

The patterns for meat and fluid in Experiment 1 were similar (Fig. 2), with most of the decrease occurring by the time that one-half of the periodic fertilizer

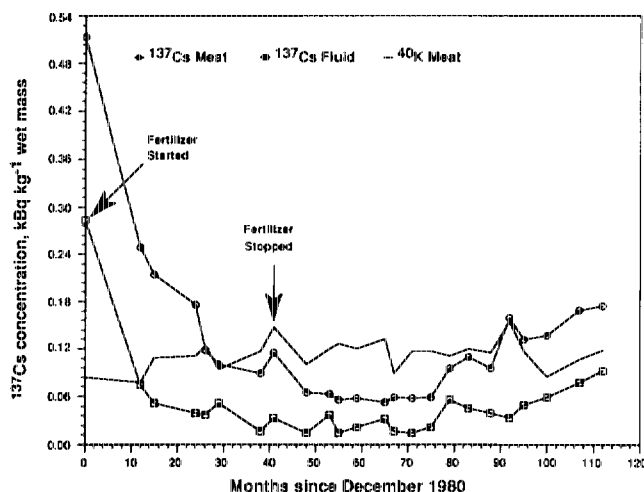


Fig. 2. Experiment I. Effect of nitrogen-phosphorus-potassium additions on mean ^{137}Cs concentrations in drinking-nut meat and fluid from three to four palms on a $26 \times 26\text{-m}$ plot. Arrows mark the beginning and end of fertilization period. Eneu Island.

additions had been made. The data shown in Fig. 2 also reveal that ^{137}Cs in meat and fluid remained below ~ 0.15 and $\sim 0.056 \text{ kBq kg}^{-1}$ (~ 4 and $\sim 1.5 \text{ pCi g}^{-1}$), respectively, for about 6 y, 4 y of which follow the final application of fertilizer. Nevertheless, a gradual but continuing increase began 3 y after that final application. Soil samples taken 19 mo after the first upturn reveal both the low organic matter at this site ($\sim 3\%$ at 0–15 cm, $\sim 1\%$ at 15–30 cm) and disappearance of added potassium (22 and 7 mg kg^{-1} exchangeable potassium at the two depths, vs. 16 and 8 mg kg^{-1} outside the plot).

Experiment IV

We attribute the abrupt decrease of ^{137}Cs visible in the controls at 9 mo, followed by appreciable recovery, to a "clearing effect" produced by extensive destruction of surface roots, plus localized shifting of the uppermost soil layers, plus off-site removal of some surface soil mixed with roots and stems of vegetation. Elsewhere, Morris et al. (1983) have quantified the loss of nutrient-rich topsoil by machine-clearing intended to remove only coarse vegetation. Such a clearing effect must also be embedded in the apparent responses to treatment.

The first posttreatment samples were collected at 9 mo, thus representing a 3–9 mo response to only three of the four scheduled fertilizer applications (Table 2). The approximate minimum concentrations of ^{137}Cs (=maximum decreases) were reached 6 mo later and remained constant until the end of the experiment at 33 mo (Fig. 5a, b). The accompanying Duncan's test results are given in Table 3.

Although without apparent effect when combined with potassium, the nitrogen-phosphorus treatment

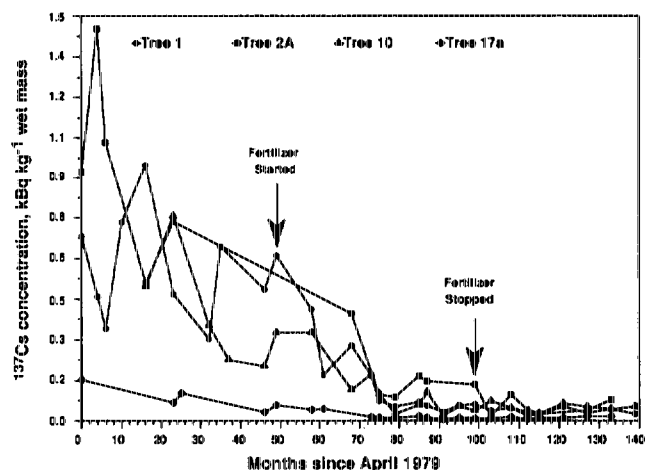
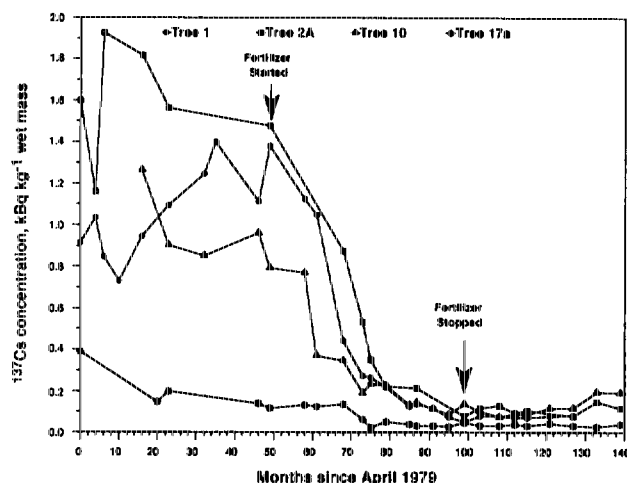


Fig. 3a. Experiment II. Effect of 13 applications of NPK on ^{137}Cs concentrations of drinking-nut meat from four palms representing the range of initial concentrations. Arrows mark the beginning and end of fertilizer application to 8.5-m radius around each palm. Eneu Island.

Fig. 3b. Experiment II. Effect of 13 applications of NPK on ^{137}Cs concentrations of drinking-nut fluid from four palms representing the range of initial concentrations. Arrows mark the beginning and end of fertilizer application to 8.5-m radius around each palm. Eneu Island.

alone reduced ^{137}Cs in meat and fluid to about one-half of the control levels (Figs. 5a, b). Both rates of potassium, with and without nitrogen-phosphorus, reduced mean ^{137}Cs to about $0.67\text{--}0.93\text{ kBq kg}^{-1}$ ($18\text{--}25\text{ pCi g}^{-1}$) in drinking-nut meat, and $0.22\text{--}0.37\text{ kBq kg}^{-1}$ ($6\text{--}10\text{ pCi g}^{-1}$) in fluid. Although some differences between rates of added potassium and/or presence of nitrogen-phosphorus attain significance ($p = 0.10$) early in the experiment and at 33 mo, the differences are minor. Essentially, the lower rate of potassium (1260 kg ha^{-1}) without nitrogen-phosphorus is as effective as the higher rate or the combinations with nitrogen-phosphate.

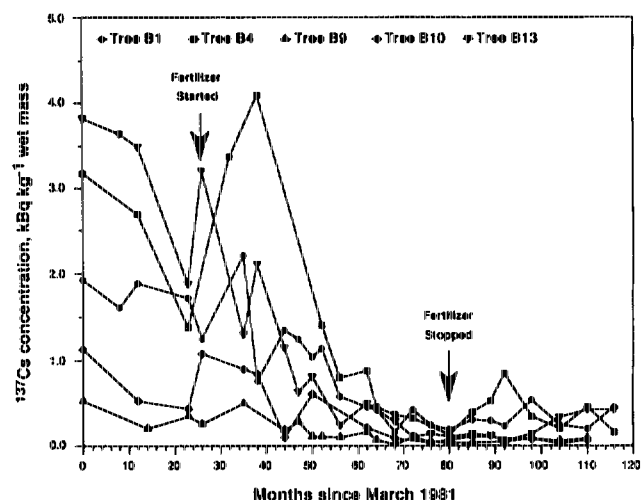
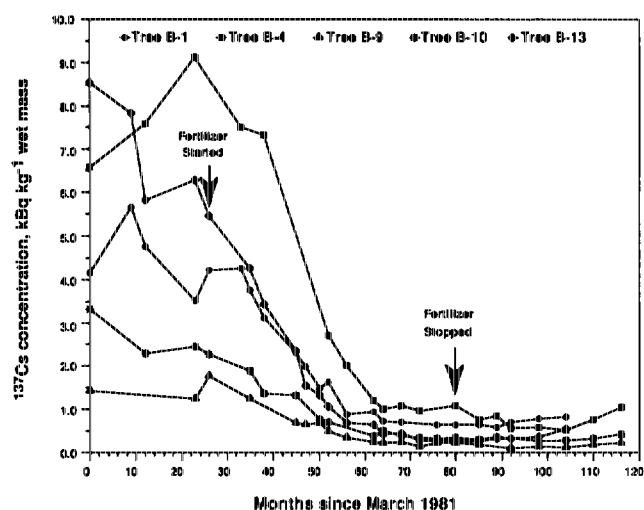


Fig. 4a. Experiment III. Effect of 13 applications of NPK on ^{137}Cs concentrations of drinking-nut meat from four palms representing the range of initial concentrations. Arrows mark the beginning and end of fertilizer application to 8.5-m radius around each palm. Bikini Island. Note difference in ordinal scales between Bikini island and Eneu Island.

Fig. 4b. Experiment III. Effect of 13 applications of NPK on ^{137}Cs concentrations of drinking-nut fluid from four palms representing the range of initial concentrations. Arrows mark the beginning and end of fertilizer application to 8.5-m radius around each palm. Bikini Island. Note difference in ordinal scales between Bikini Island and Eneu Island.

Samples collected at 42 mo reveal that doubling the fertilized width of the two K_1 pilots 9 mo earlier had further decreased ^{137}Cs in drinking-nut meat by 0.22 or 0.3 kBq kg^{-1} (6 or 8 pCi g^{-1}). This modest decrease is evidence of root activity outside the originally fertilized 8.5-m band on either side of the sampled row. Likewise, ^{137}Cs in the K_0NP measurement row, now only 8.5 m distant from potassium-treated soil on

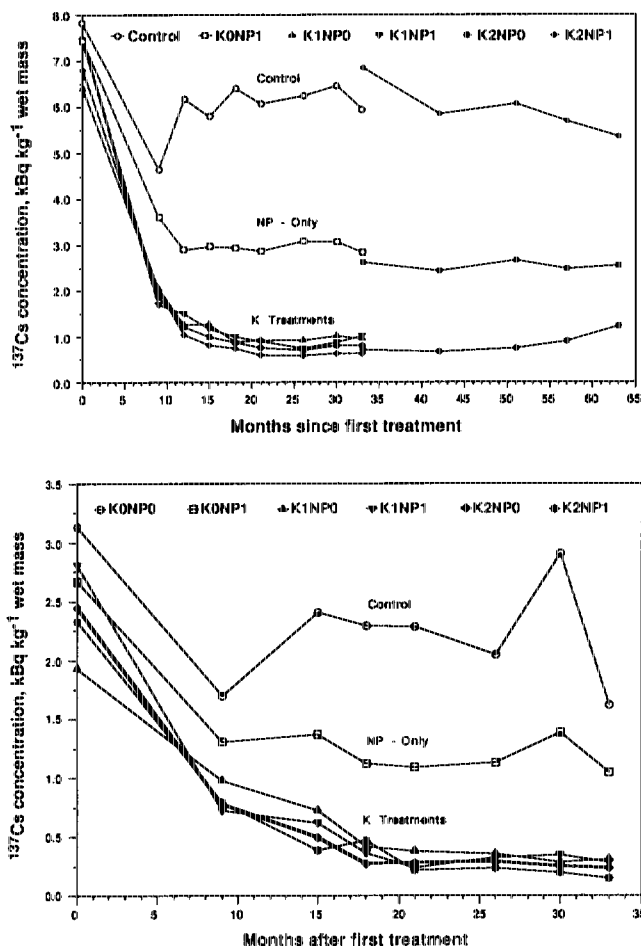


Fig. 5a. Experiment IV. Response of drinking nut ^{137}Cs concentrations to 0, 1260, and 2520 kg ha $^{-1}$ potassium (K₀, K₁, K) and/or combined nitrogen-phosphorus treatment, applied as four equal additions over 9 mo. Values to 33 mo are weighted plot means (See Table 3). Values for 33–63 mo (solid symbols) are means ($n = 6$ to 10) from single plots unaffected by further treatment.

Fig. 5b. Experiment IVa. Response of drinking-nut fluid concentrations of ^{137}Cs in same experiment as 5a.

either side, decreased from ~3 to 1.7 kBq kg $^{-1}$ (~80 to 45 pCi g $^{-1}$).

Thus, interpretation of the 42-mo ANOVA must be limited to comparison of the control and K₂ treatments, neither of which was affected by plot width increases. The respective means for K₀NP₀, K₂NP₀, and K₂NP₁ are 5.3, 0.78, and 0.59 kBq kg $^{-1}$ (142, 21, and 16 pCi g $^{-1}$) for drinking-nut meat and 2.1, 0.32, and 0.22 kBq kg $^{-1}$ (56, 8.6, and 6.0 pCi g $^{-1}$) for fluid. All differences among the three values are significant by Duncan's multiple range test ($p = 0.10$). The latter finding concurs with results of the Duncan's tests at 33 mo (Table 3) and suggests that a small additive effect of the nitrogen-phosphorus treatment may be emerging.

Results from the three unreplicated plots of the original Experiment IV indicate that the effects of nitrogen-phosphorus and K₂ persist unchanged to about 53 mo (Fig. 5a). Thereafter, the suppressive effects of K₂ appear to diminish and ^{137}Cs in drinking-nut meat from the K₂ treatment increases to 1.2 ± 0.19 kBq kg $^{-1}$ (33 ± 5 pCi g $^{-1}$) at 63 mo (Table 4).

Copra nuts

At 42 mo, concentrations of ^{137}Cs in drinking-nut meat over all treatments ranged from ~0.37 to 7.4 kBq kg $^{-1}$ (~10 to ~200 pCi g $^{-1}$). Paired samples of drinking nuts and copra nuts from individual palms yielded the following regressions (expressed as kBq kg $^{-1}$, wet mass):

$$^{137}\text{Cs} \text{ (copra-nut meat)} = 1.60 \times ^{137}\text{Cs} \text{ (drinking-nut meat)}, R^2 = 0.97 \quad (1)$$

$$^{137}\text{Cs} \text{ (copra-nut fluid)} = 0.52 \times ^{137}\text{Cs} \text{ (copra-nut meat)}, R^2 = 0.96. \quad (2)$$

Grass and moonvine

Little grass was evident on the plots before the initial clearing, so the mixed grass cover present at 9 mo had spread from persistent stolons and seeds germinating after the first appreciable rains, 7 mo previously. Hard seeds of the deep-rooted moonvine are omnipresent. As with coconut, the 9-mo samples were collected just before the last of four equal fertilizer applications (Table 2).

The effects of treatment on ^{137}Cs concentration on the above-ground mass of grass resembled those on coconut over a period of 30 mo, except for an initial decline in the controls from 83.3 to 28.5 kBq kg $^{-1}$ (2250 to 770 pCi g $^{-1}$, dry weight) (Fig. 6). After 30 mo, however, ^{137}Cs in both the controls and nitrogen-phosphorus treatments increased sharply, with less fluctuation thereafter. Mean concentrations in the eight potassium-treated plots were initially very low, ~1.85 kBq kg $^{-1}$ (~50 pCi g $^{-1}$, dry mass) but also increased markedly after 30 mo (Fig. 6), indicating a diminishing effect of treatment. Further changes after 45 mo are confounded by applications of potassium to seven of the eight previously potassium-treated plots and to one of the nitrogen-phosphorus plots (described under Experiment VIII). This application reduced ^{137}Cs to 2.2 and 8.3 kBq kg $^{-1}$ (59 and 225 pCi g $^{-1}$, dry mass), respectively, whereas the remaining untreated plot values converged to a mean of ~38 kBq kg $^{-1}$ (~1030 pCi g $^{-1}$, dry mass).

Early observations indicated a denser grass cover on those plots receiving nitrogen-phosphorus. Fig. 7 (a and b) gives no indication, however, that ^{137}Cs concentrations have been "diluted" by greater mass.

Unlike grass, ^{137}Cs in moonvine from the control plots did not decline in the successive collections at 9, 18, and 21 mo. Nor were there clear trends of changes with time for the other treatments. Accordingly, values for the two replicates and three dates were combined as were those for potassium applications with and with-

Table 3. Experiment IV. Results of Duncan's multiple range tests ($p = 0.10$) for ^{137}Cs concentration in drinking-nut meat and fluid.

	Sample date—months after first application								
	0	9	12	15	18	21	26	30	33
Meat									
<i>Main Effects</i>									
K_0	A*	A	A	A	A	A	A	A	A
K_1	A	B	B	B	B	B	B	B	B
K_2	A	B	C	C	B	B	B	B	C
NP_0	A	A	A	A	A	A	A	A	A
NP_1	A	B	B	B	B	B	B	B	B
<i>Simple Effects</i>									
K_0NP_0	A	A	A	A	A	A	A	A	A
K_0NP_1	AB	B	B	B	B	B	B	B	B
K_1NP_0	B	C	DC	C	C	C	C	C	C
K_1NP_1	AB	C	C	C	C	C	C	C	CD
K_2NP_0	AB	DC	D	D	C	C	C	C	DE
K_2NP_1	AB	D	D	D	C	C	C	C	E
Fluid									
<i>Main Effects</i>									
K_0	---	A	A	A	A	A	A	A	A
K_1	---	B	B	B	B	B	B	B	B
K_2	---	B	C	C	B	B	B	B	B
NP_0	---	A	A	A	A	A	A	A	A
NP_1	---	A	A	B	B	B	B	B	B
<i>Simple Effects</i>									
K_0NP_0	---	A	A	A	A	A	A	A	A
K_0NP_1	---	BC	B	B	B	B	B	B	B
K_1NP_1	---	B	D	CD	C	C	C	C	CD
K_2NP_0	---	C	D	DE	C	C	C	C	D
K_2NP_1	---	C	D	E	C	C	C	C	E

* Within sample date (column), values represented by the same letter do not differ significantly. See Figs. 5a, b.

out nitrogen-phosphorus. The resulting means \pm standard errors (SEM) follow:

$$K_0 (n = 5) \quad 3.3 \pm 0.37 \text{ kBq kg}^{-1} \quad (3)$$

(green mass)

$$K_0 + NP (n = 6) \quad 1.2 \pm 0.15 \text{ kBq kg}^{-1} \quad (4)$$

$$K_1 \pm NP (n = 12) \quad 0.63 \pm 0.11 \text{ kBq kg}^{-1} \quad (5)$$

$$K_2 \pm NP (n = 12) \quad 0.52 \pm 0.074 \text{ kBq kg}^{-1} \quad (6)$$

Hence, treatment effects in moonvine generally parallel those for grass and coconut. ^{137}Cs in moonvine leaves from the control and nitrogen-phosphorus plots is much lower than in grass (when both are expressed on a wet mass basis), probably because moonvine roots are less concentrated in the surface layer.

^{40}K measurements in both species indicated higher total potassium concentrations in the 9-mo collections, followed by declines. Accordingly, results from treatments and sample dates were aggregated to provide sufficient sample sizes for testing. Thus, the following means (\pm SEM) are for K_0 over all sample dates, $K_1 + K_2$ at 9 mo, and K_1 and K_2 again at either 15 and 18, or 15, 18, and 21 mo combined. The respective values (expressed as g kg^{-1} , green mass) are 3.9 ± 0.4 , 6.3 ± 1.0 , and 3.9 ± 0.15 , for grass, and 1.4 ± 0.2 , 4.3 ± 0.4 , and 2.4 ± 0.2 for moonvine.

Thus, at 9 mo, after application of only 75% of the

scheduled amount of potassium, potassium concentrations had increased nearly two-fold in grass and three-fold in moonvine. By about month 18 to month 20, however, plant concentration had returned to about the control level. Almost certainly this decrease was at least hastened by a period of excess rainfall, 1,090 mm, in months 18–20. No large changes in ^{137}Cs accompanied this reduction.

Experiment V

ANOVAs over the entire treatment period indicate that decreases in ^{137}Cs in both meat and fluid are significant at $p = 0.012$. With one exception, ANOVAs for individual sampling dates show significant treatment effects, mostly at $p = 0.05$ to 0.01 , beginning at 6 mo (meat) or 9 mo (fluid) after the single, large application of potassium. Levels of ~ 0.56 and $\sim 0.22 \text{ kBq kg}^{-1}$ (~ 15 and $\sim 6 \text{ pCi g}^{-1}$) in meat and fluid, respectively, persist for at least 30 mo (Fig. 7a, b).

The initial decline of ^{137}Cs in the control means cannot be due to a "clearing effect" inasmuch as site preparation, other than subsoiling to create single-palm plots, had occurred 1 y previously. The range of ^{137}Cs concentration from ~ 1.5 to 7.4 kBq kg^{-1} (~ 40 to 200 pCi g^{-1}) prior to any treatment indicates that soil ^{137}Cs is distributed irregularly, that is, its distribution is patchy relative to the scale of the rooting radius. It appears that subsoiling, by severing all the roots outside

Table 4. Experiment VIII. Mean ^{137}Cs concentration in drinking-nut meat from the same individual palms before, and 12 mo after, application of potassium to subdivisions of the former Experiment IV area.

Potassium (kg ha ⁻¹)		Number of trees	¹³⁷ Cs (kBq kg ⁻¹ , wet mass)		Phosphorus
Treatment ^a					Significance of difference
0-9 mo	51 mo		51 mo	63 mo	
<i>Controls</i>					
0	0	14	4.9	4.7	Not significant
0 + nitrogen-phosphorus	0	4	2.7	2.6	Not significant
2,520	0	8	0.74	1.2	<0.001
<i>Re-treated^b</i>					
1,260	1,120	11	0.85	0.41	<0.0005
1,260 + nitrogen-phosphorus	1,120	16	0.78	0.41	<0.0005
2,520	1,120	18	1.1	0.48	<0.0005
2,520 + nitrogen-phosphorus	1,120	15	0.59	0.33	<0.0005

^a The 0, 1,260, and 2,520- kg ha^{-1} treatments correspond to individual K_0 , K_1 , and K_2 plots, respectively, in Table 3 and Fig. 5.

^b Re-treatment extended beyond the Experiment IV plot boundaries so that all or most of the roots were in potassium-treated soil.

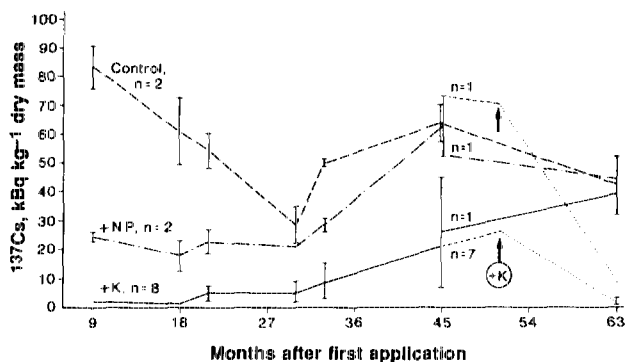


Fig. 6. Experiment IV. Changes in ^{137}Cs concentration (dry mass basis) in an understory grass, *Eustachys petraea*, following: 1) application of potassium (\pm nitrogen-phosphorus) or nitrogen-phosphorus alone at 0, 3, and 6 mo; and 2) reapplication of potassium (K) (arrows) at 48 mo to seven plots previously treated with potassium and one nitrogen-phosphorus plot. Dotted lines indicate subsequent courses. Vertical lines indicate range around mean.

the 8.5×8.5 -m-squares, eliminated uptake from some nearby patches of soil high in ^{137}Cs .

The effective time required for major reduction in treated plots was less than the 9 mo indicated by Figs. 7a and b inasmuch as the fertilizer was broadcast on dry soil (only 14 mm rainfall in the previous mo) and only 42 mm fell in the succeeding 2 mo. Thus, penetration of potassium into the upper soil was delayed. Nevertheless, first indications of a decrease in ^{137}Cs appear in the 3-mo samples.

No obvious symptoms of stress appeared in coconuts subjected to the severe pruning of lateral roots, plus application of potassium-chlorine at the rate of 12,500 kg ha^{-1} over the residual root system, plus limited rainfall in the following 2 mo.

Experiment VI

The single, moderately large application of potassium (3940 kg ha^{-1}) was made to palms that averaged only $\sim 0.67 \text{ kBq kg}^{-1}$ ($\sim 18 \text{ pCi g}^{-1}$) in drinking-nut meat. This mean was reduced to $\sim 0.26 \text{ kBq kg}^{-1}$ ($\sim 7 \text{ pCi g}^{-1}$) over a period of 15 mo (Fig. 8). Fluid concentrations were likewise lowered to a mean of only $0.067 \text{ kBq kg}^{-1}$ (1.8 pCi g^{-1}), which approximates activity due to the natural content of ^{40}K .

The pattern of slow and gradual decrease contrasts with those of the other experiments. Relatively constant levels in the adjacent control plot demonstrate that the less drastic site preparation procedures employed had avoided any "clearing effect," such as noted for Experiment IV.

Experiment VII

Experiment VII is similar in design to Experiment VI, and only about 270 m distant, but differs in response (Fig. 9). Before treatment, ^{137}Cs concentrations in drinking-nut meat averaged about 4.8 kBq kg^{-1} (130 pCi g^{-1}). After application of $670 \text{ kg potassium ha}^{-1}$ —the lowest total applied in these experiments— ^{137}Cs fell to $\sim 1.4 \text{ kBq kg}^{-1}$ ($\sim 38 \text{ pCi g}^{-1}$) in 9 mo and to $\sim 0.96 \text{ kBq kg}^{-1}$ ($\sim 26 \text{ pCi g}^{-1}$) after 15 mo.

Experiment VIII

Fifty-one mo after the initial addition of potassium to palms in Experiment IV (42 mo after the final addition), mean ^{137}Cs in drinking-nut meat ranged between 0.59 and 1.1 kBq kg^{-1} (16 and 30 pCi g^{-1}). Following a second application of $1,120 \text{ kg potassium ha}^{-1}$, mean values in the same palms decreased to 0.33 to 0.48 kBq kg^{-1} (9 to 13 pCi g^{-1}) at 63 mo (Table 4). Neither the level of potassium nor the addition of nitrogen-phosphorus in the original treatment had any further effect.

A similar decrease appears in the paired means

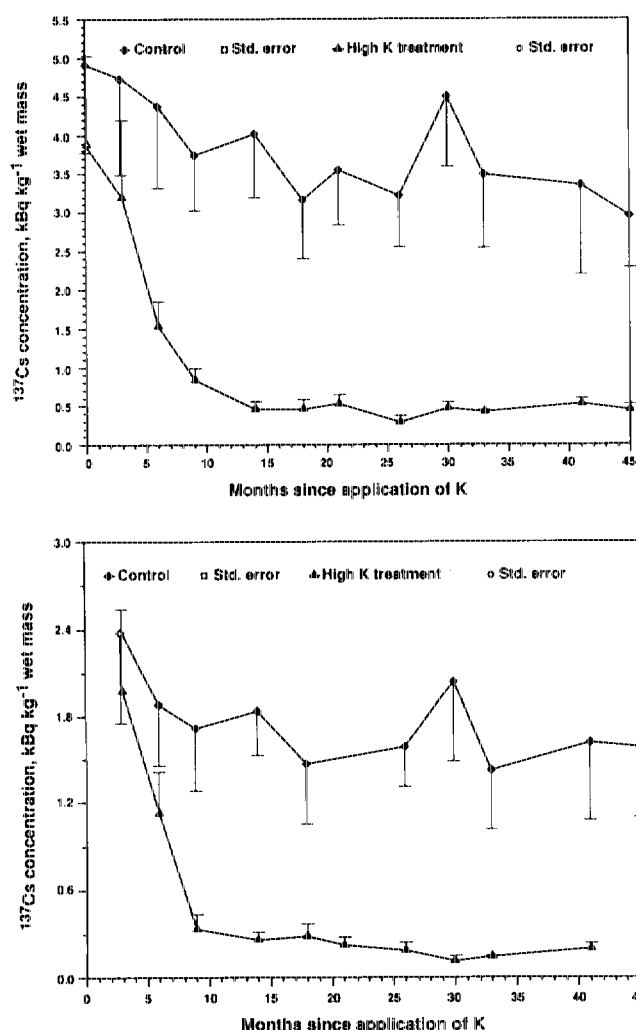


Fig. 7a. Experiment V. Response of ^{137}Cs concentrations in drinking-nut meat after application of 6,270 kg potassium ha⁻¹ to single palm plots. The bars indicate one SEM ($n = 3$ to 5).

Fig. 7b. Experiment V. Response of ^{137}Cs concentrations in drinking-nut fluid after application of 6,270 kg potassium ha⁻¹ to single palm plots. The bars indicate one SEM ($n = 3$ to 5).

from 67 palms representing eight border rows (hence, fertilized on one side originally) that were subsequently fertilized on the opposing side at 33 mo, and then retreated. The mean (\pm standard deviation) concentration of 0.80 ± 0.28 kBq kg⁻¹ (21.5 ± 7.6 pCi g⁻¹) at 51 mo fell to 0.42 ± 0.10 kBq kg⁻¹ (11.3 ± 2.8 pCi g⁻¹) at 63 mo.

In contrast to these decreases, ^{137}Cs remained essentially unchanged over this period in the palms not treated with potassium (Table 4). Those initially treated with potassium at 2,520 kg ha⁻¹ but untreated thereafter, actually increased from 0.75 ± 0.17 kBq kg⁻¹ to 1.2 ± 0.18 kBq kg⁻¹ (20 ± 4.6 to 33 ± 4.9 pCi g⁻¹) at

63 mo. The increase, indicating a decline in suppressive effect of the initial potassium additions, comes after a long period of relatively stable ^{137}Cs concentrations, as shown by the unpaired means for this treatment (Fig. 5a). This decline follows a second period of unusually high rainfall, with a total of ~1,100 mm for months 52 through 55 (June through September 1989).

DISCUSSION

Potassium effects in coconut

The patterns of ^{137}Cs reduction following potassium application are similar for drinking-nut meat, drinking-nut fluid, and older copra nut meat, although ratios among these vary with relative nut maturity. The similarity of response to potassium and to potassium plus nitrogen-phosphorus treatments (Figs. 5a, b) suggests that the reduction of ^{137}Cs in Experiments I, II, and III (Figs. 2, 3, 4) is due solely to the potassium component of the mixed nitrogen-phosphorus-potassium fertilizers applied. This indication is confirmed by the large reductions following other potassium-only treatments (Figs. 7, 8, 9).

Over all first-application experiments, the absolute decreases in drinking-nut ^{137}Cs due to potassium are greater where initial concentrations are greater, regardless of total amount of potassium applied. When the decreases are expressed as percentages of pretreatment concentrations, however, all fall between 60 and 90%. In this case of Experiments IV, V, and probably Experiment VII (Figs. 5, 7, and 9), such values (75, 89, and 81%, respectively) include some effect of clearing or subsoiling at installation of the study. Percentage decreases of ^{137}Cs in fluid are similar to those in meat. Perhaps coincidentally, the decreases following reapplication of potassium at 51 mo averaged about 50% (Table 4).

The time required for a major decrease in ^{137}Cs concentration in drinking nuts after potassium application is about 9 mo in Experiments V and VII (Figs. 7 and 9), or somewhat less in the former when the lack of rain after treatment is considered. A comparable period of low rainfall after the first potassium application to Experiment IV probably influenced the time for major decreases (Figs. 5a and b) there also. Little is known, however, about the possible storage or turnover rates of potassium and cesium in the large masses of foliage and parenchymatous stems of bearing coconut.

Development from flower to mature copra nut occurs over a period of about 1 y. The 9-mo requirement for ^{137}Cs reduction, indicated previously, concurs with the probable time for development of a "modal drinker" plus allowance for penetration and uptake of potassium applied to the soil surface. Thus, this requirement is not greatly affected by the quantity of potassium applied, within the range examined here—670 to 6,300 kg potassium ha⁻¹ (Table 2).

In view of the above, the much longer time for near-maximum decrease of ^{137}Cs in Experiments I, II,

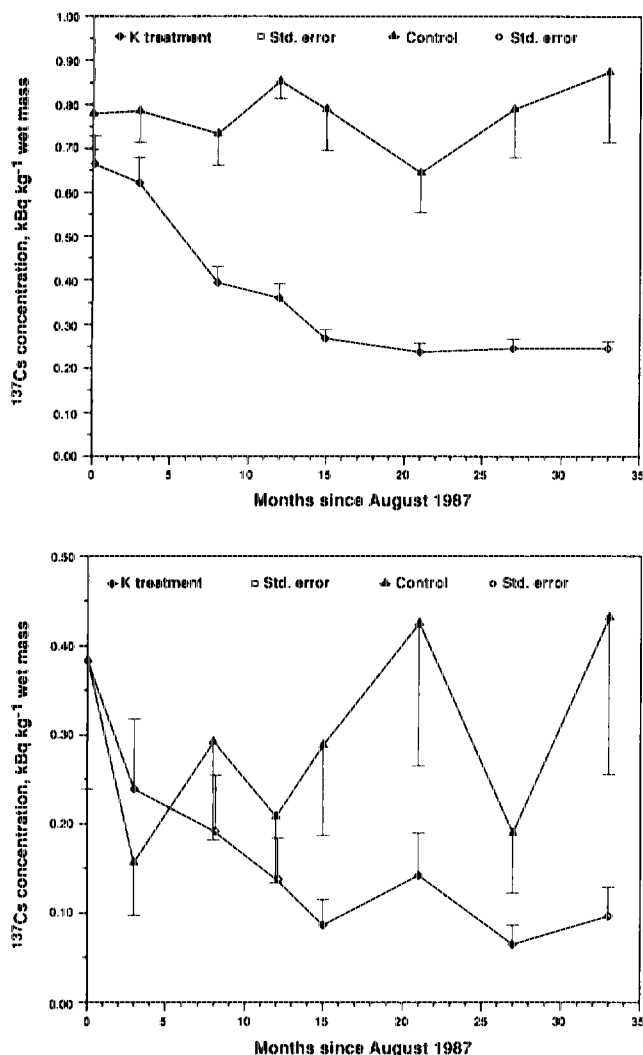


Fig. 8a. Experiment VI. Effect of 3,740 kg potassium ha⁻¹ applied in August 1987 on palms with low concentrations (~0.75 kBq kg⁻¹) in drinking-nut meat. The bars indicate one SEM for six to nine palms per plot.

Fig. 8b. Experiment VI. Effect of 3,740 kg potassium ha⁻¹ applied in August 1987 on palms with low concentrations (~0.75 kBq kg⁻¹) in drinking-nut fluid. The bars indicate one SEM for six to nine palms per plot.

and III likely is due to a slow net accumulation of potassium from the approximately quarterly applications. In Experiment I (Fig. 2), all fertilizer was added as plastic-encapsulated pellets, which delayed full solubility. Further, the first two applications were made during the dry winter period. In Experiments II and III (Figs. 3 and 4) only 40% of the applied potassium was plastic-encapsulated. More consequentially, however, nitrogen-phosphorus-potassium fertilizers were broadcast repeatedly over an 8.5-m radius around individual palms, favoring development of absorbing root masses by intruding lateral roots from surrounding palms. The

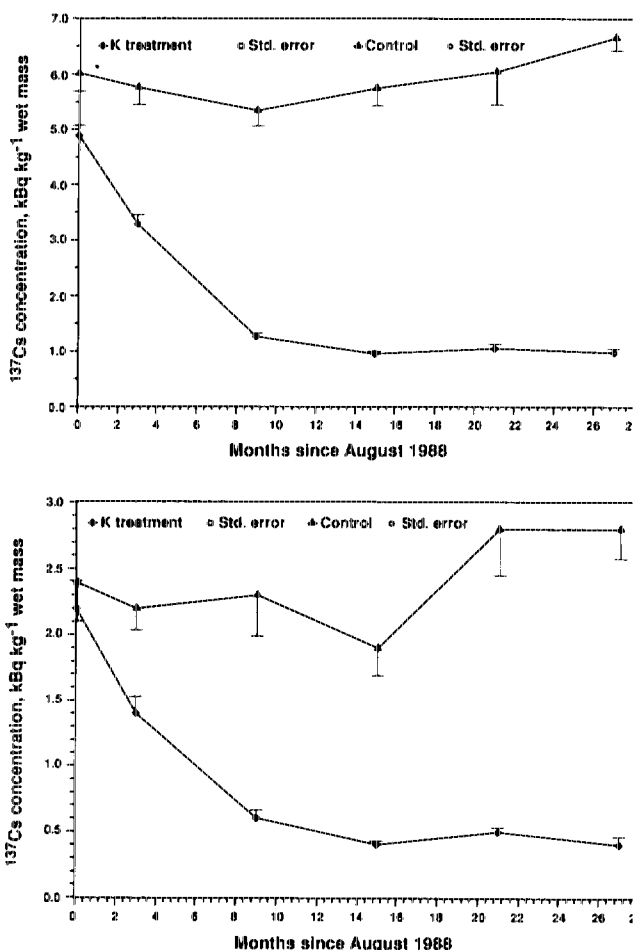


Fig. 9a. Experiment VII. Effect of 670 potassium ha⁻¹ applied August 1989 on ^{137}Cs concentration in drinking-nut meat. The bars indicate one SEM for 12 to 16 palms per plot.

Fig. 9b. Experiment VII. Effect of 670 kg potassium ha⁻¹ applied August 1989 on ^{137}Cs concentration in drinking-nut fluid. The bars indicate one SEM for 12 to 16 palms per plot.

resulting redistribution of successive applications over a much larger area would have reduced their effectiveness on the target palms. Such "poaching" by surrounding trees is a known problem in orchard fertilization research (Haines et al. 1954).

Duration of potassium response

Once attained, the maximum reduction in ^{137}Cs (i.e., maximum response to potassium) persists for periods up to at least 30–45 mo (Fig. 5 and Table 4). In Experiment I (Fig. 2), the small but continuing increase in ^{137}Cs , beginning 36 mo after the last fertilizer application, probably signals an end to the suppressive effect of potassium, although that of phosphorus may then emerge. The first upturn in ^{137}Cs occurred about 9 mo after the exceptionally high cumulative rainfall of August through October 1986 (1,090 mm on Bikini Is-

land), which would have accelerated normal soil leaching.

^{137}Cs in grass and moonvine

Reduction of ^{137}Cs in grass following potassium application (Fig. 6) agrees with an earlier report from Rongelap Atoll by Walker et al. (1961) but is larger and of longer duration. They had applied potassium-chlorine at the rate of 130 kg potassium ha^{-1} to a 0.005-ha plot of a different grass, *Lepturus repens* (Frost. f.), beneath coconut. Seven mo later, ^{137}Cs in grass had decreased from 1.1 to 0.28 kBq kg^{-1} (29.5 to 7.5 pCi g^{-1} , dry mass), as compared with a control, whereas potassium had increased from 3.9 to 6.4 g kg^{-1} . These differences disappeared in the next 6 mo, presumably because the relatively small addition was dissipated through uptake by roots of surrounding palms and, perhaps, by leaching.

In the present study, the decrease of ^{137}Cs in the controls between 9 and 30 mo somewhat obscures the similarity of response in coconut and grass. A likely cause for this large decrease is competition from redeveloping coconut roots in the disturbed soil surface. This is also suggested by recovery of drinking-nut ^{137}Cs concentration after 9 mo (Fig. 5a).

Mechanism of cesium suppression by potassium

The mechanism(s) by which soil-applied potassium suppresses ^{137}Cs in the fruit of coconut is unknown. Paired plot comparison of ^{137}Cs surface-gamma emission across boundaries between control and potassium-treated plots gave no evidence that potassium had displaced ^{137}Cs from the surface soil. A more plausible and apparently widely accepted explanation is competition between the two ions for root uptake (Shaw and Bell 1989). Conceptual difficulties arise, however, when the disparity between concentrations of the two ions in Bikini soils and the modest increases in potassium brought about by even heavy applications are considered. The range of exchangeable potassium in Bikini soils is from $\sim 2.6 \times 10^{-4}$ to 10^{-3} mol kg^{-1} , whereas total ^{137}Cs ranges from about 10^{-12} to 10^{-11} mol kg^{-1} . Only about 3% of this total appears to be exchangeable (Koranda et al. 1978; Robison et al. 1988). Application of 1,000 kg potassium ha^{-1} , distributed to a depth of 10 cm, amounts to about 2.6×10^{-2} mol kg^{-1} . Such an addition overwhelms the existing levels of exchangeable potassium but increases the already wide disparity between potassium and cesium by only 1 or 2 orders of magnitude. The suppressive effects of this potassium increase on ^{137}Cs in plants, however, are profound. Moreover, the ion-competition hypothesis, as formulated, cannot be readily reconciled with certain field observations. In Experiment IV, the mean decreases in drinking-nut ^{137}Cs at 33 mo for palm rows bordering K_1 rows (hence fertilized on only one side) were about 90% as great as for palms fertilized on both sides, rather than 50%. Hypotheses that would account for such an effect are yet to be tested.

Nevertheless, further observations in these same rows and others demonstrate that increasing the area of potassium-treated soil around palms with unconfined root systems further lowers ^{137}Cs concentrations in nuts. The results of Experiment VIII (Table 4) concur with such observations, although the effects of the enlarged treatment area in this case cannot be separated from those due to increasing potassium concentration within the original plot boundaries.

Phosphorus effects

The unanticipated $\sim 50\%$ reduction in ^{137}Cs (Figs. 5a, b) following the nitrogen-phosphorus treatment has been duplicated in a less-extensive study nearby. The reductions have been maintained for more than 63 mo in both studies. The latter observations suggest that phosphorus rather than nitrogen is the effective element inasmuch as unabsorbed nitrogen is rapidly lost from such soils whereas all phosphorus is retained.

As with potassium, there is no certain explanation of how phosphorus suppresses uptake of cesium. The following results from other studies are suggestive in combination: 1) Coconut roots are known to be colonized by vesicular-arbuscular (VA) mycorrhizae (Thomas and Ghai 1987; Thomas 1988) and examinations of roots from Bikini confirm abundance of internal hyphae; 2) As noted by Sylvia and Neal (1990), accounts of phosphorus suppressing root colonization by VA fungi in other species are numerous, although there are also accounts of no effect and of selection for phosphorus-tolerant fungi on high phosphorus soils. Sylvia and Neal's own studies with onion demonstrated suppressive effects of added phosphorus when internal supplies of nitrogen were sufficiently high; and 3) Colonization of roots by VA mycorrhizae has increased uptake of cesium as well as cobalt (Rogers and Williams 1986). Whether similar processes are operative in large palms growing in atoll soils is yet to be examined.

APPLICATION OF RESULTS

We have not determined the minimum quantities of potassium required for maximum effectiveness of ^{137}Cs suppression in bearing groves with a ground cover of grass and herbs. Moreover, our experimental areas are not systematically harvested, which would entail an appreciable annual loss of potassium. In Experiment VII (Fig. 9), however, addition of 670 kg potassium ha^{-1} over the entire root system rapidly reduced ^{137}Cs in drinking-nut meat from a mean of ~ 4.8 to ~ 1.1 kBq kg^{-1} (~ 130 to ~ 30 pCi g^{-1}). Application of 1,260 kg potassium ha^{-1} to palms initially higher in ^{137}Cs , 6.3 to 7.4 kBq kg^{-1} (170 to 200 pCi g^{-1}), lowered these levels to ~ 0.93 kBq kg^{-1} (~ 25 pCi g^{-1}) or less (Fig. 5), and somewhat further when treatment width was expanded from 8.5 to 17 m on either side of the row. Neither doubling the rate of potassium nor combination with nitrogen and phosphorus had any certain effect in further reducing ^{137}Cs over a 33-mo period (Fig. 5).

The lag time between application of potassium and the major, not necessarily maximum, reduction of ^{137}Cs in drinking-nut meat and fluid is 8 to 9 mo, or somewhat longer if a rainless period follows application. This time seems independent of potassium rate, above some level of adequacy. The minimum level of ^{137}Cs attained through single applications of potassium is influenced by the pretreatment level. It is probably affected by amount of applied potassium at or near the lower limits of adequacy but apparently not above $1,200 \text{ kg ha}^{-1}$. Distribution of the applied potassium over the whole area of the root system seems to achieve maximum reduction, but reduction is not proportional to the percentage of root area treated.

Once achieved, the reduction can persist for at least 36–63 mo after application, although perhaps diminishing slowly (Fig. 2 and Table 4). The effects of lower rates likely will persist for shorter times. The main determinants of persistence, however, are probably the total amount of soil organic matter, which retains potassium, and the amount of excess rainfall leaching through the soil. For this reason, scheduling applications of $600\text{--}1,000 \text{ kg potassium ha}^{-1}$ at 3-y intervals may prove more effective and cost efficient than larger applications at longer intervals.

Coconut palms have a high requirement for potassium, both through the juvenile development stage and to meet the needs of nut production and harvest removals. Applications suggested for tall varieties are in the range of $1\text{--}3 \text{ kg palm}^{-1} \text{ y}^{-1}$, or $135\text{ to }410 \text{ kg ha}^{-1} \text{ y}^{-1}$ at $8.5\text{--} \times 8.5\text{-m}$ spacing. At such rates, the cumulative 3-y addition for production purposes would approach or overlap our suggested application of $600\text{--}1,000 \text{ kg ha}^{-1}$ every 3 y to suppress ^{137}Cs uptake, thus achieving both purposes.

Present knowledge of the suppressive effects of potassium on ^{137}Cs , especially the interactions with rainfall, is incomplete. It is, therefore, desirable that application of potassium to reduce ^{137}Cs in human or domestic animal diets be accompanied by periodic monitoring to assure that the expected results are attained.

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Errata

McInroy, J. F.; Gonzales, E. R.; Miglio, J. J. Measurement of thorium isotopes and ^{228}Ra in soft tissues and bones of a deceased Thorotrast patient. *Health Phys.* 63(1):54-71; 1992.

The authors and editorial staff regret an error in the spreadsheet used for the calculation of the thorium and radium concentrations of the ribs (1-12) reported in Table B-6 (page 69). The corrected values are:

Table B-6. Weights, thorium isotopes and radium concentrations of bones and parts of bones of the entire skeleton.

Skeletal part	Weight (g)		Thorium and radium concentration (Bq kg ⁻¹ ash)			
	Wet	Ash	^{232}Th	^{228}Ra	^{228}Th	^{230}Th
Ribs (1-12)	448	131	7179	3150	2764	908

All other numbers in the table remain the same.

We apologize for any inconvenience or confusion these errors may have caused the readers of *Health Physics*.



Errata

Robison, W. L.; Stone, E. L. The effect of potassium on the uptake of ^{137}Cs in food crops grown in coral soils: Coconut at Bikini Atoll. *Health Phys.* 62(6):496-511; 1992.

The authors and editorial staff regret that a typographical error went undetected throughout the review of this paper. On page 500, a conversion was listed as 1.0 Bq $^{40}\text{K} \approx 22.27$ mg potassium; the correct conversion is 1.0 Bq $^{40}\text{K} \approx 32.8$ mg potassium. We apologize for any inconvenience this error may have caused the readers of *Health Physics*.



